In-space Nondestructive Inspection Technology Workshop

End-User Needs: Composite Pressure Vessel/ Rocket Propulsion Inspections

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Overview

- NDE needs for Composite Pressure Vessels and composite pressurized structures
  - Manufacturing and Acceptance Testing
  - In-situ Structural Health Monitoring
  - Stress rupture and other testing

- NDE needs for Rocket Propulsion Inspections
  - Liquid Propellant Engines and Components
  - Solid Propellants
  - Pyrotechnic Devices
  - Propulsion Testing

NDE needs for Composite Pressure Vessels & Composite Pressurized Structures

Background

Problems:

- COPVs can be at risk for catastrophic failure
  - Risk of insidious burst-before-leak (BBL) stress rupture[1] (SR) failure of carbon-epoxy (C/Ep) COPVs during mid to late life
  - Risk of impact damage lowering burst strength of C/Ep COPVs
  - Failure at lower pressure than previous proof cycle pressure
- Issues with manufacturing defects and inspectabilty of COPVs on NASA spacecraft (ISS, deep space)
- Lack of quantitative NDE is causing problems in current and future spacecraft applications
  - Thinner liners are driving need for better flaw detection in liner and overwrap
  - Must increase safety factor or accept more risk

[1] SR defined by AIAA Aerospace Pressure Vessels Standards Working Group as “the minimum time during which the composite maintains structural integrity considering the combined effects of stress level(s), time at stress level(s), and associated environment”

Background cont'd

The NASA Engineering and Safety Center (NESC) conducted two major COPV Technical Assessments (concerns were passed on to associated programs)

- NDE was not adequately implemented during Shuttle and ISS COPV manufacturing and provisions were not made for on-going COPV structural integrity or health checks
- "Stress rupture" of ISS C/Ep COPVs is a major concern
  - Stress rupture failure of gas pressurized COPVs on the ground or in flight presents a catastrophic hazard

Background cont'd

Fundamental NDE gaps identified at the September 2009 *Composite Pressure Vessel and Structure Summit* are still relevant (over 120 attendees, including Joint NASA, DOD/DOE/FAA, industry, and academia).

High level needs were identified:

1. Need qquantitative rather than qualitative NDE for composites applications. Physical defect standards are critical and must be directly representative of the structure being inspected.

2. Need NDE inspections integrated into the manufacturing process to ensure significant flaws do not exist and to ensure consistency
   - NDE is needed to avoid a catastrophic failure on NASA spacecraft, ensure other critical criteria requirements are met such as "Safe-Life"[1]

[1] The required period of time or number of cycles that the metallic liner of a COPV, containing the largest undetected crack shown by analysis or testing, will survive without leaking or failing catastrophically in the expected service load and environment (AIAA-S-080A)

COPV Issues

- COPVs studied from 2005 – 2010 still demonstrated a relatively large amount of variability in burst pressure and stress rupture progression rate.
  - Some recently reviewed indicated approx. 4% for T1000 and 7-9% for IM7, on burst
    - Other test vessels have indicated even greater variability

- NDE processes need to be integrated into manufacturing to reduce this variability and improve quality

- NDE is desired at each major step from fabrication through qualification

COPV Issues cont'd

- Inspection concerns that need consideration at each major step from fabrication through qualification:
  - Crack and grain boundary issues from liner spinning operation
  - As-manufactured strain distribution and liner deformation/buckling issues following autofrettage
  - Excessive vessel growth after autofrettage indicating “out-of-family” low modulus
  - Liner-to-composite adhesive disbonds and gaps from CTE mismatch during thermal cure
  - Composite weak areas from poor wetting or out gassing during cure, resulting in porosity
  - Bridging during winding
  - Tow tension issues resulting in excessive fiber breakage during autofrettage

Near-term ASTM NDE Standards

- ASTM E07 writing committees are documenting mature, current, and “state-of-the-art” practices and test methods for COPV metallic liners, composite overwraps, and composite-to liner-interface
  - Standards to date in the backup charts
  - Other promising, but less mature methods will be placed on a list for NNWG or NESC to evaluate and mature
  - Due to the scope, teaming with government and industry of common interest is needed to add expertise and resources

Technique Development

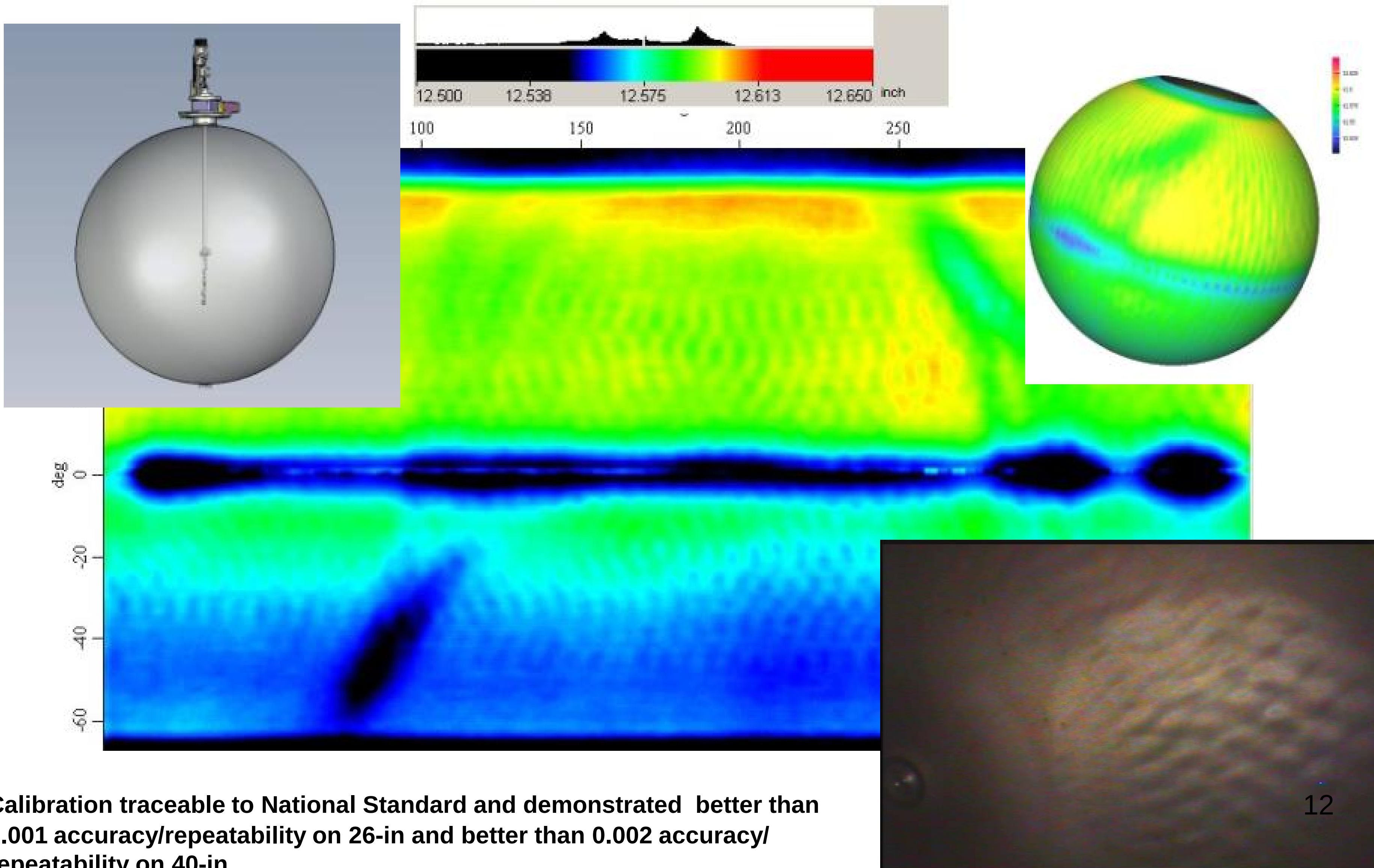
- Promising, but less mature methods need evaluation and maturation, but progress has been slow:
  - Evaluation of flaw detection capability is occurring at the coupon level in coordination with on-going JSC/NNWG physical standards program, but COPV liner progress continues to be slow
  - NESC/NNWG expects to do development of automated techniques as funding is available
  - Progress has been made at LaRC on detection of natural flaws and flaws grown by pressure cycling
  - WSTF project is also quantifying flaw detection using our new custom Laser Techniques Company eddy current (EC) scanner, comparing 4 new Uniwest probes (next section)
    - Limited POD will be conducted if successful (coordination and assistance from LaRC)

Other Recent Progress

- Excellent progress made on Laser Profilometry that add eddy current and other capabilities (e.g., UT) to form a universal COPV Manufacturing NDE Scanner
  - Highlights in next few slides

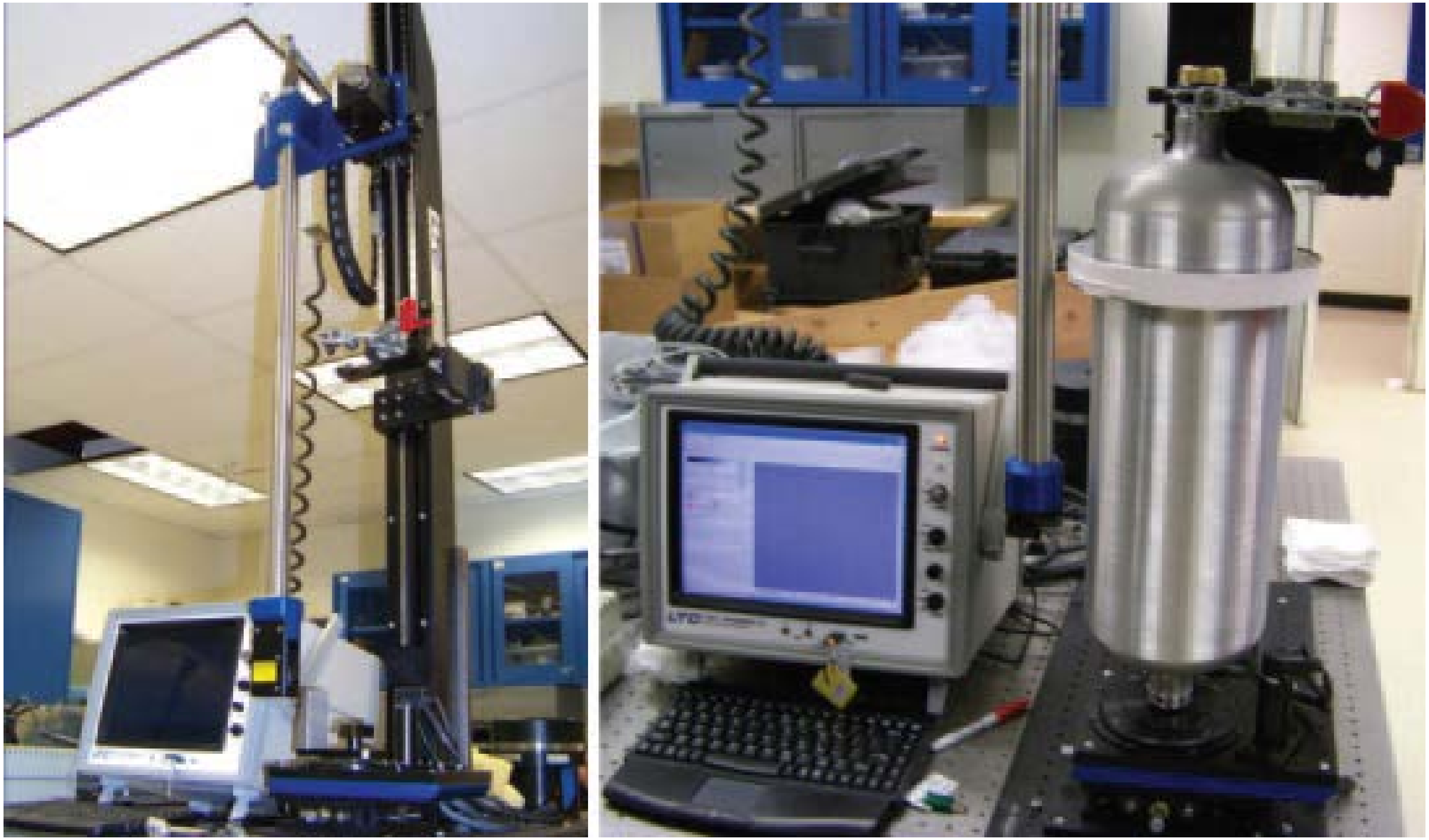
- Excellent progress also made with Shearography, but needs additional definitive physical standards and a POD study accomplished, with various composite defects being interrogated

Laser Profilometry of COPV interior surface quantifies liner buckling which is difficult to inspect by other methods



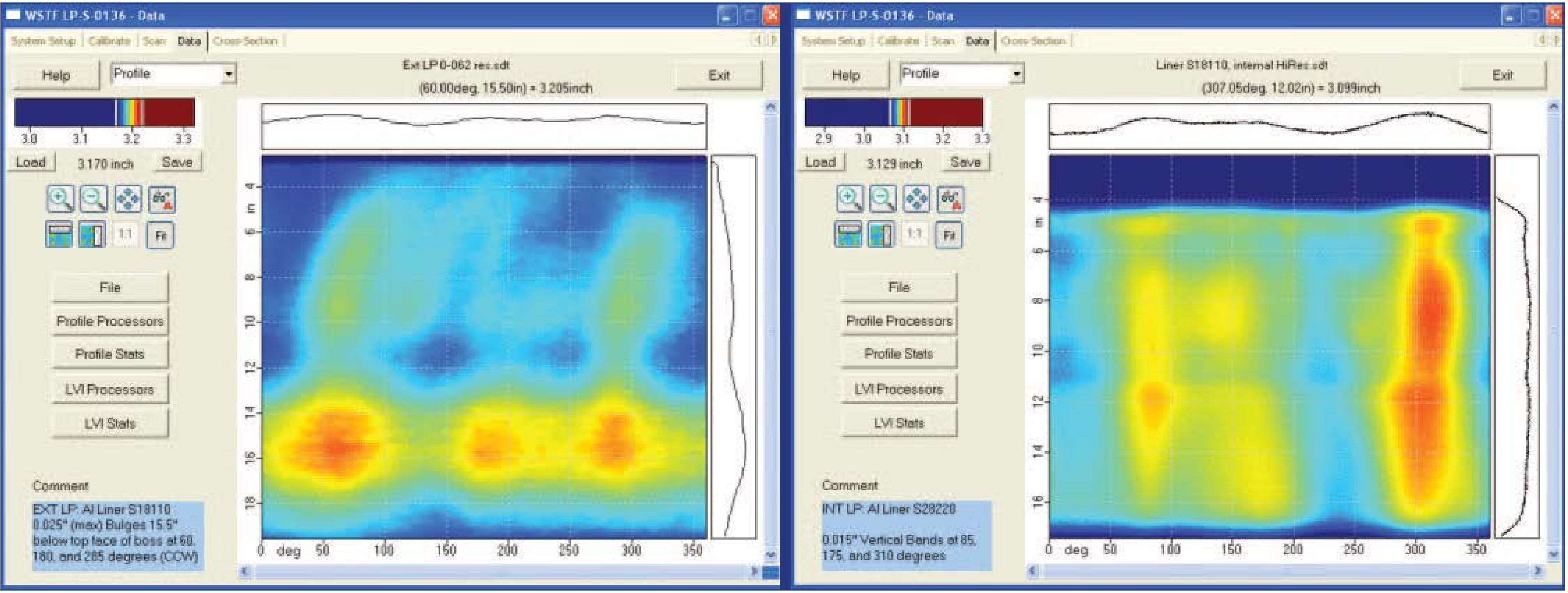
Calibration traceable to National Standard and demonstrated better than 0.001 accuracy/repeatability on 26-in and better than 0.002 accuracy/ repeatability on 40-in

Scanning for Manufacturing



External scanner calibration using NIST-traceable standard (left) and scan of liner defect standard (right).

Scans of NNWG Vessel following Stress Rupture testing



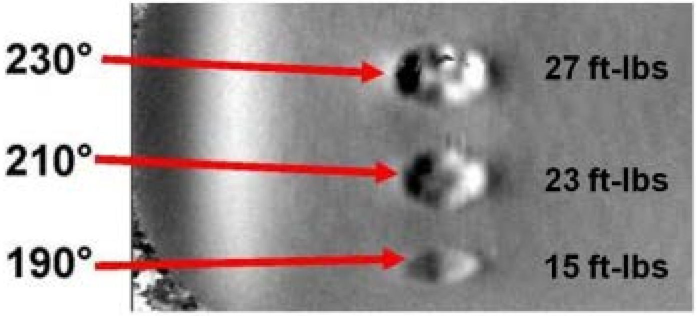
Internal (left) and external (right) radial scans of the same vessel.

Second Generation Laser Profilometry

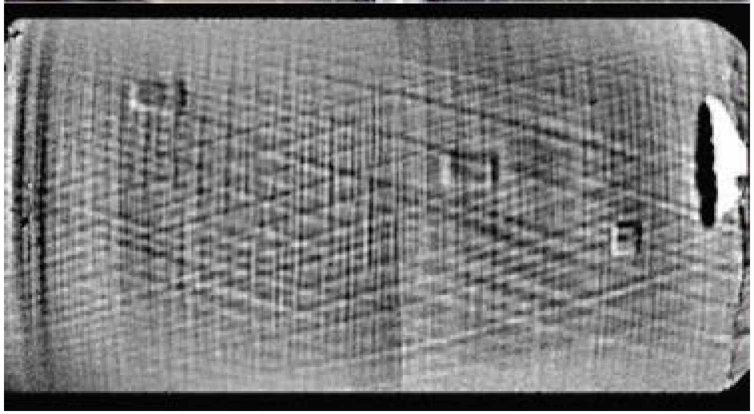
New articulated sensor allows scanning of Ellipsoidal ends

High Definition Shearography

- The LTI-5100HD Advanced Shearography System, equipped with a TES-200 thermal excitation unit, has greatly improved the ability to baseline the received stress state and monitor and identify visually undetectable subsurface impact damage.
  - The current need is to correlate damage to response and do POD studies



Pressure shearograph of COPV impacts delivered using a 0.5 in. ball-end tup



Composite overwrapped pressure vessel inspection (top) and thermal shearograph of a vessel with delaminations and a void (bottom)

The Need For Monitoring

Under the leadership of NASA Office of the Chief Technologist (OCT), NASA assessed future needs and developed roadmaps.

- These roadmaps are to be central to the planning and development of NASA space technologies critical to space exploration
- Future NASA missions may not be successful without SHM (ref. OCT Roadmaps)

Need to target the Reliability/Life Assessment/Health Monitoring in Roadmap TA12, Materials, Structures, Mechanical Systems and Manufacturing Materials, Structures, Mechanical Systems and Manufacturing and build systems supporting other discipline road maps.

- TA07, Human Exploration Destination Systems discusses the criticality of having integrated health monitoring/management systems to free up the crew to cope with other mission issues. The necessary specialized software development for this is also deemed critical.
- TA02, In-Space Propulsion Technologies discusses the criticality of having integrated systems health management (ISHM)

Enable precautionary or preemptive steps to minimize or obviate the risk of catastrophic failure

Monitoring Background

Current needs and applications include C/Ep COPVs used on ISS, the new ISS Nitrogen-Oxygen Recharge System (NORS), the Orion Crew and Service Modules, and as planned for application to nearly all future NASA spacecraft missions

- Incidental benefits also exist for COPVs used in DOT liquid natural gas and hydrogen storage applications
- Other composite structures of interest are load bearing, fracture critical composite materials used in DoD, commercial aerospace and NASA applications

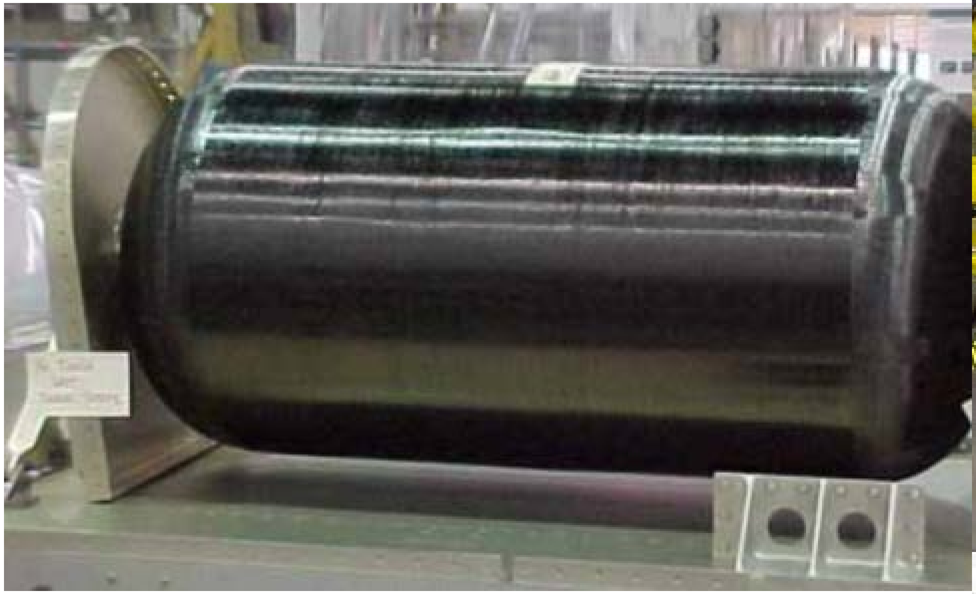
COPV Rupture Effects on ISS

COPV System	ISS Systems Destroyed	ISS Systems Severely Damaged	Hull Breech[i]	Astronaut Fatality[ii]	TNT equiv. (lbm)	Housed Internal/External
HPGT	Airlock	ISS Structure, Node 1, PV Array, TCS Radiator	Very High	Very High	8.9	External: Airlock (4), ELC pallet (2 spares)
NTA	ATA, PMA	S1/P1 Truss, PV Array, TCS Radiator, ELC pallet	High	High	3.9	External: S1 Truss (1), P1 Truss (1), ELC pallet (2-spares)
PCU	PCU Enclosure	Z1 truss, ELC1	Low	Low	0.6	External: Z1 Truss (2), ELC pallet (1-spare)
SAFER	SAFER Unit	Interior of Airlock	High	Very High (EVA), High (Hull)	0.15	Internal : Airlock (Storage) External: EVA (Operation)
SPACE-DRUMS (GBA)	GBA Housing	EXPRESS RACK, KIBO or NODE 3	High	High (EVA)	0.12	Internal: KIBO (Temporary) External: NODE 3 (Final location)
AMS CO2	AMS	PV Array, TCS Radiator, ELC pallet, AMS Xenon	Low	Low	0.4	External: AMS, S1 Truss
AMS Xenon	AMS	PV Array, TCS Radiator, ELC Pallet, AMS CO2	Low	Low	0.6	External: AMS, S1 Truss
VCAM	VCAM Unit	None	Very Low	Very Low	0.01	Internal: EXPRESS RACK
VGA	VGA Unit	None	Very Low	Very Low	0.01	Internal: EXPRESS RACK
GBU-Ar GBU-He GBU-CO 2	CGSE (COPV Storage Compartment)	Common Gas Supply Unit	Low	Low (Hull)	0.06 0.06 .02	Internal: KIBO

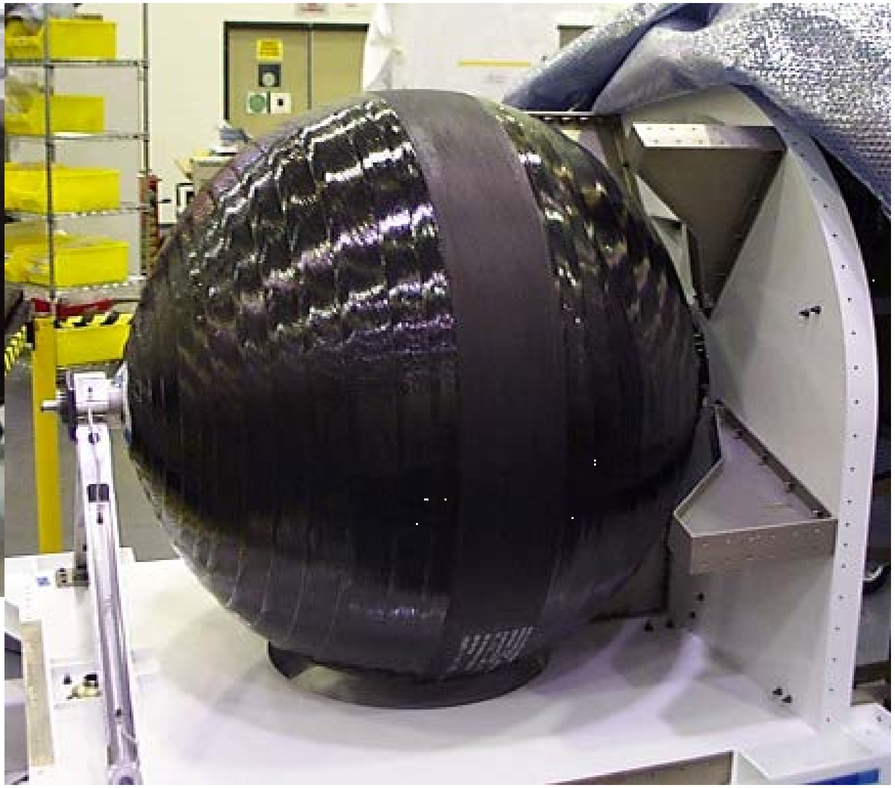
[i] Classifications are based on the following percentages: Very High (>75%), High (75%-25%), Low (25%-5%) and Very Low (<5%)

[ii] Classifications are based on the following percentages: Very High (>75%), High (75%-25%), Low (25%-5%) and Very Low (<5%). The designation 'Hull' designates that the potential for astronaut fatality would be a consideration only if the hull were breached. The designation EVA only refer to only the crew member (or members) performing EVA.

ISS Vehicle COPV Configurations



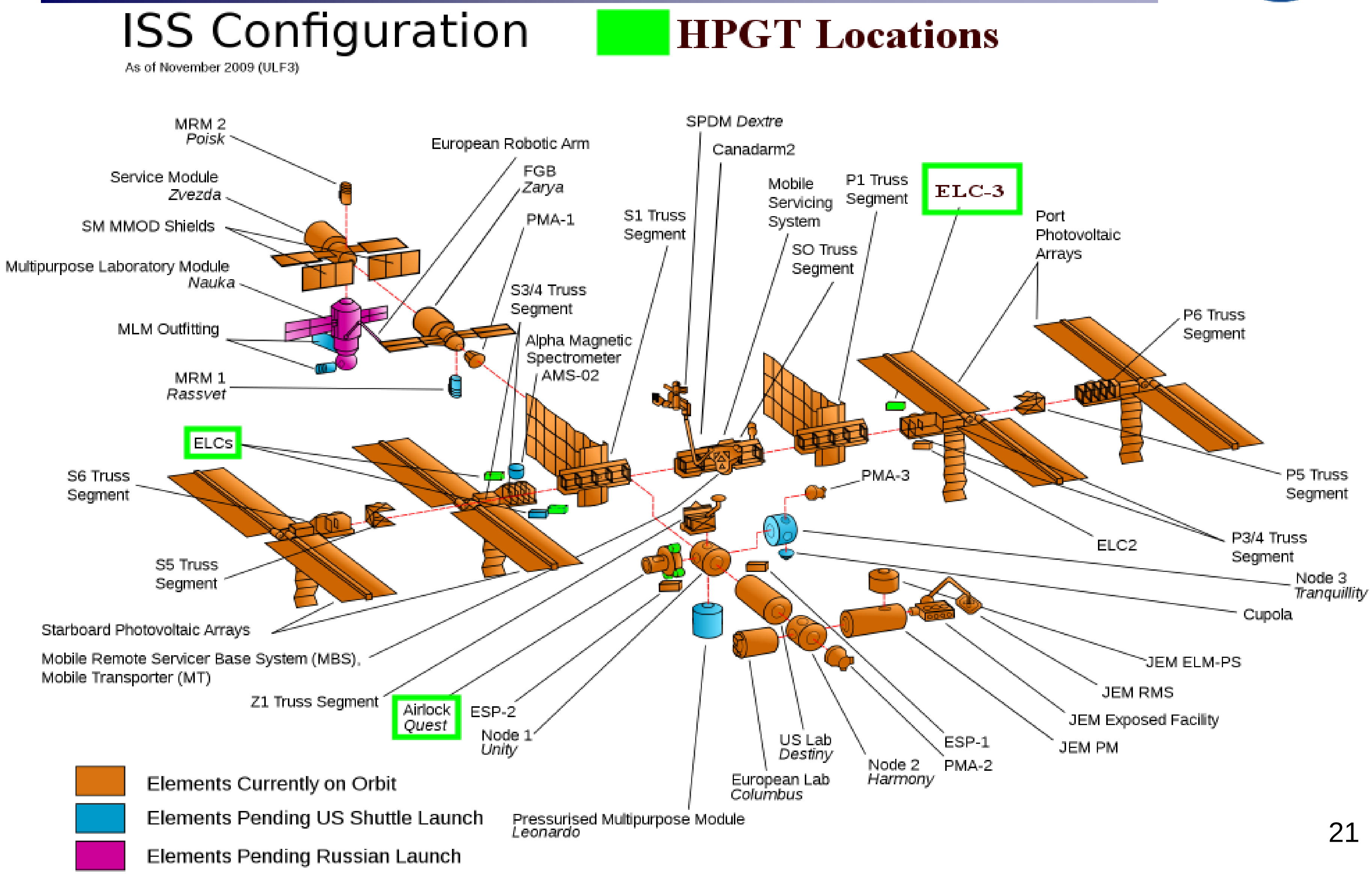
Nitrogen Tank Assembly (45”Lx19.7”D)



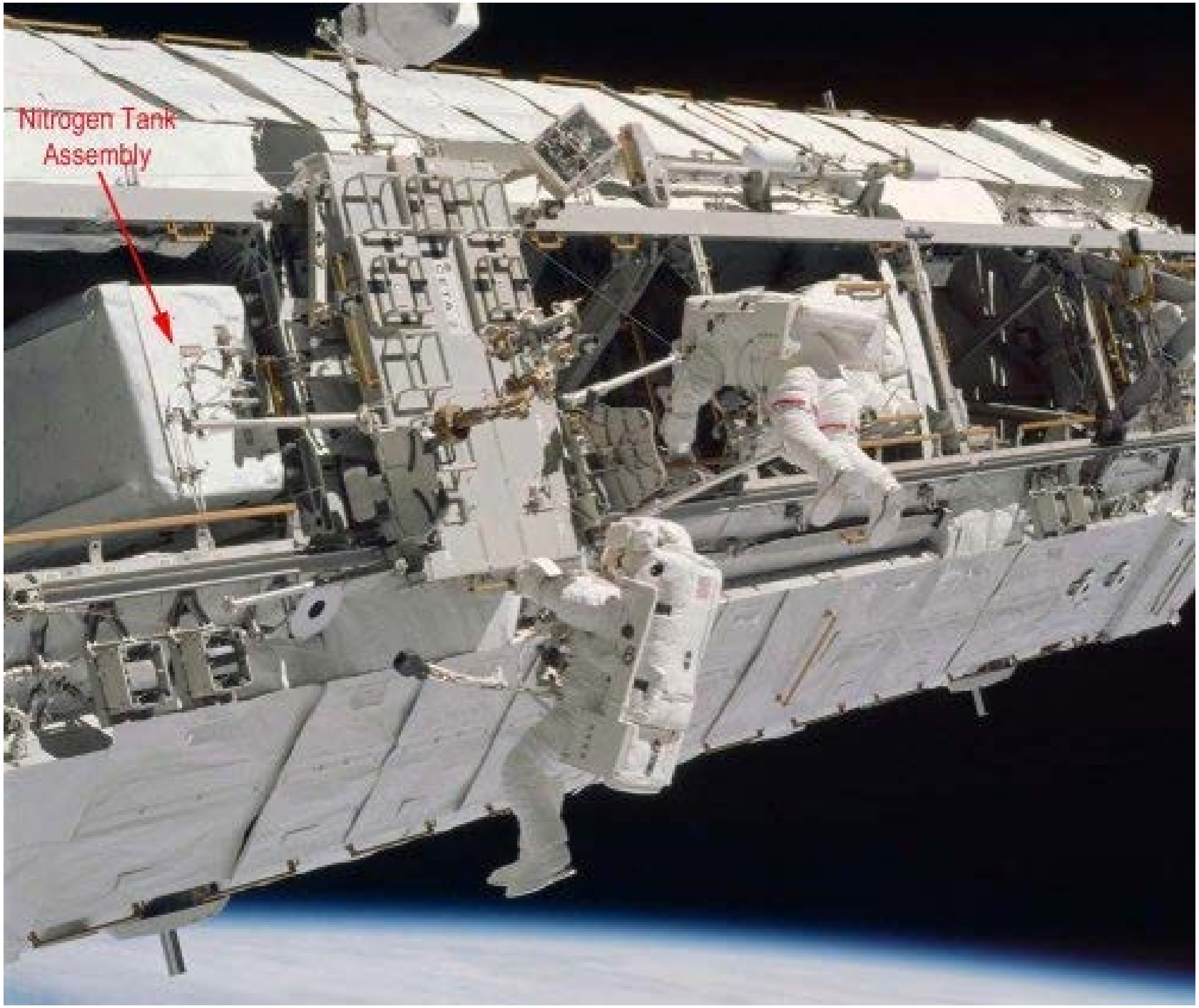
HPGT COPV (37.89”D)

ISS COPV Information is courtesy of
Scott C. Forth (JSC-ES411)

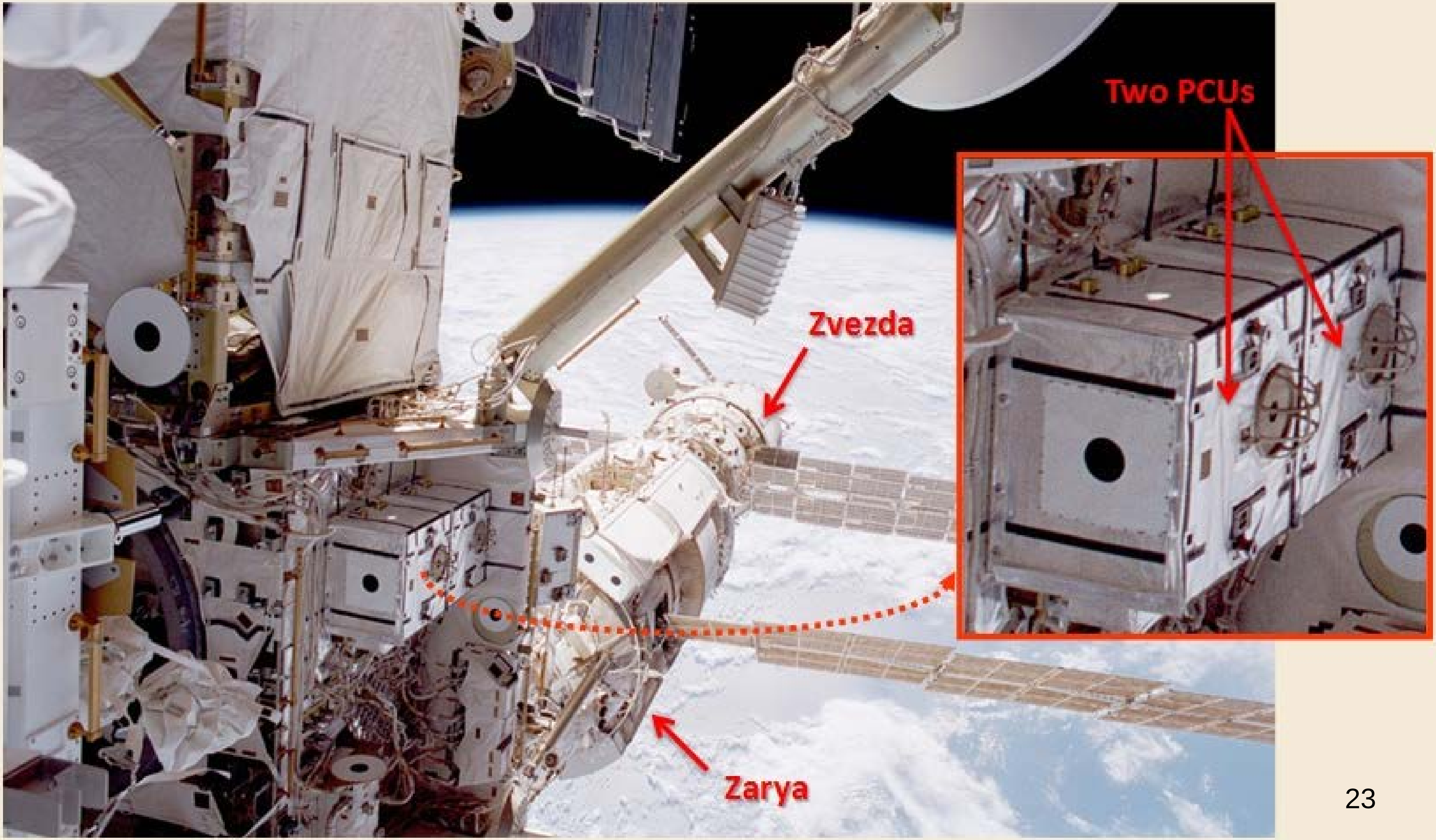
ISS Vehicle COPVs



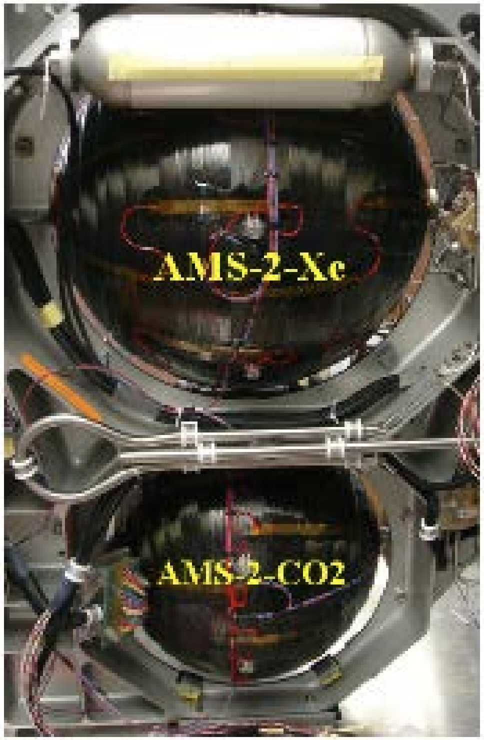
Nitrogen Tank Assembly



Plasma Contactor Unit



ISS Payloads, Experiments, Systems



NASA photos

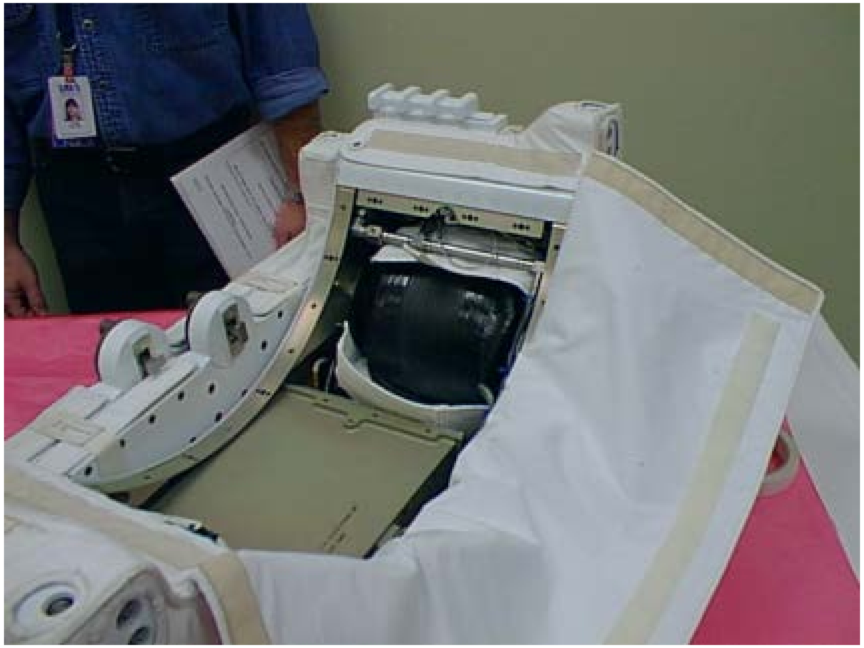
AMS

Six GBUs in Kibo

Space DRUMS

SAFER

NASA photo

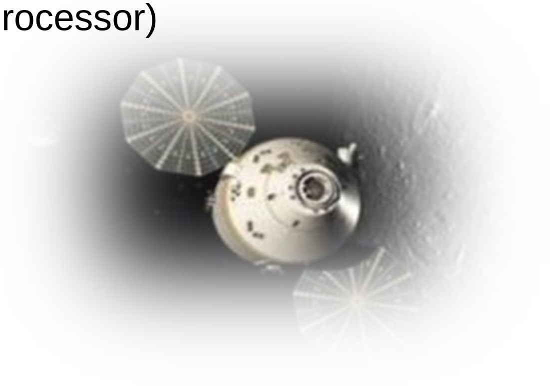


SAFER (9”Lx6.6”D)

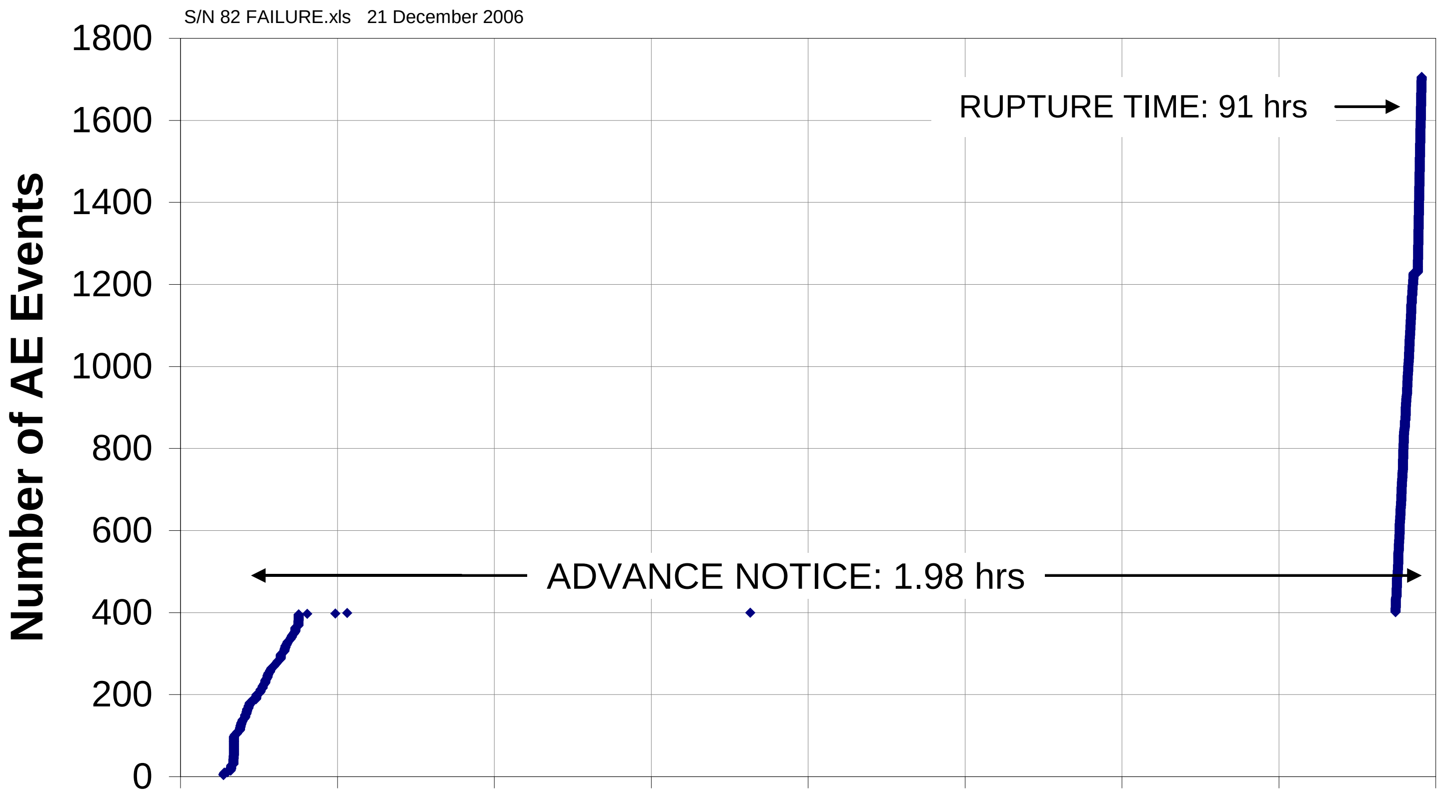
Integrated COPV SHM

- It is desireable to integrate SHM sensors into COPVs during manufacturing creating “Smart” COPVs:
  - The first step is to make better COPVs with less variability as a foundation for “Smart” COPVs using inspection techniques like the Profilometer and Eddy Current scanning systems

- The “Smart” COPV project is being initiated based on several promising Structural Health Monitoring (SHM) techniques and projects:
  - Advancements have been made by team participants in coordination with NASA's Lightweight Spacecraft Structures & Materials (LSSM) and several other precursor programs (i.e. Active UT methods)
  - Stress rupture NDE Development project developments
  - Multi-axial FBG Systems for Real-time NDE Inspection project
  - Acousto-Optics development project
  - In-situ Carbon Fiber Micromechanics project develops acoustic emission trends (accumulation, Felicity ratio, wavelet feature trend analysis via. NDE Wave and Image Processor)
  - Eddy Current strain measurement of COPVs

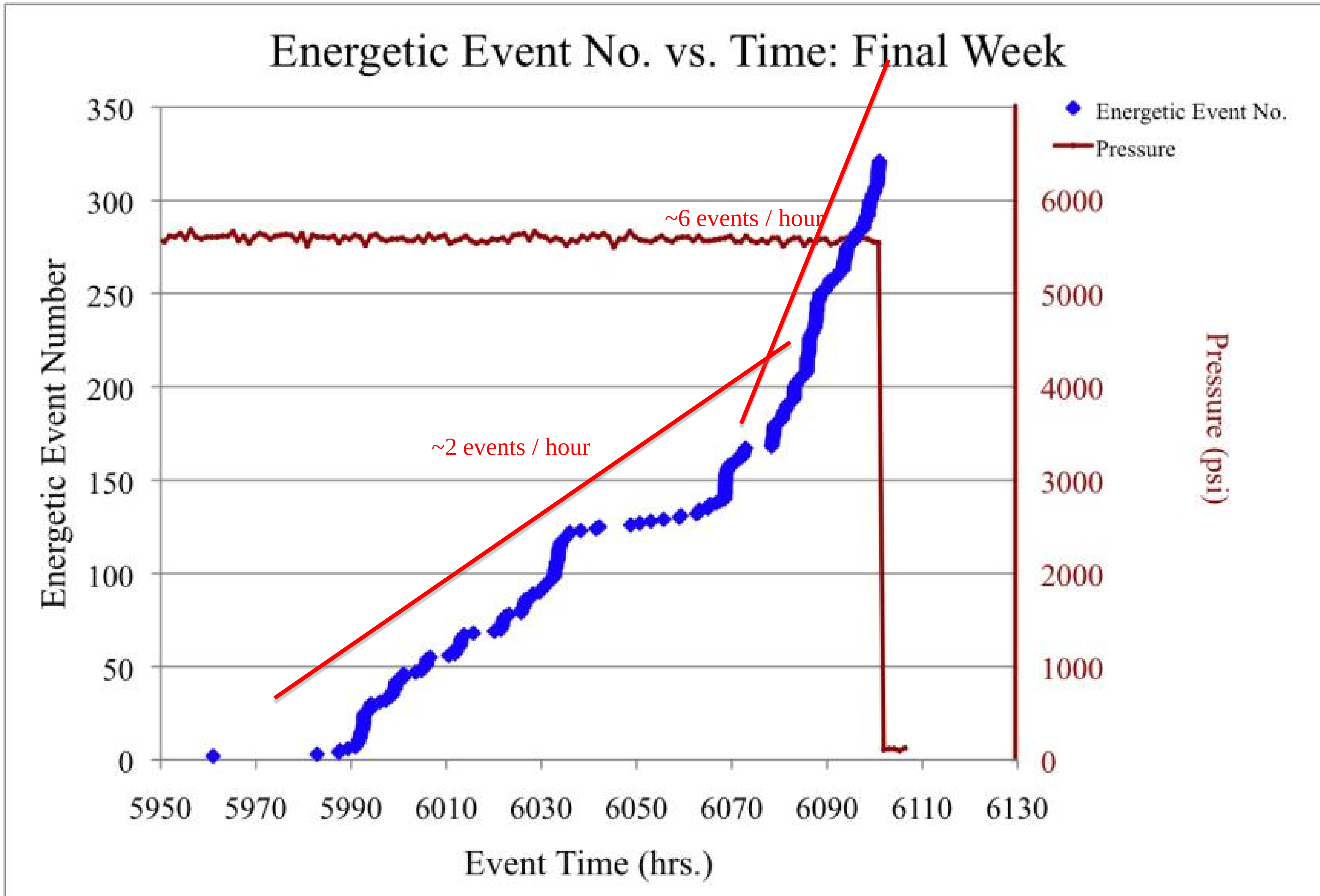


Example AE Results



AE indications begin to accumulate well before rupture occurs. The synchronization of these data to strain and temperature indications will be accomplished in the next phase of our project

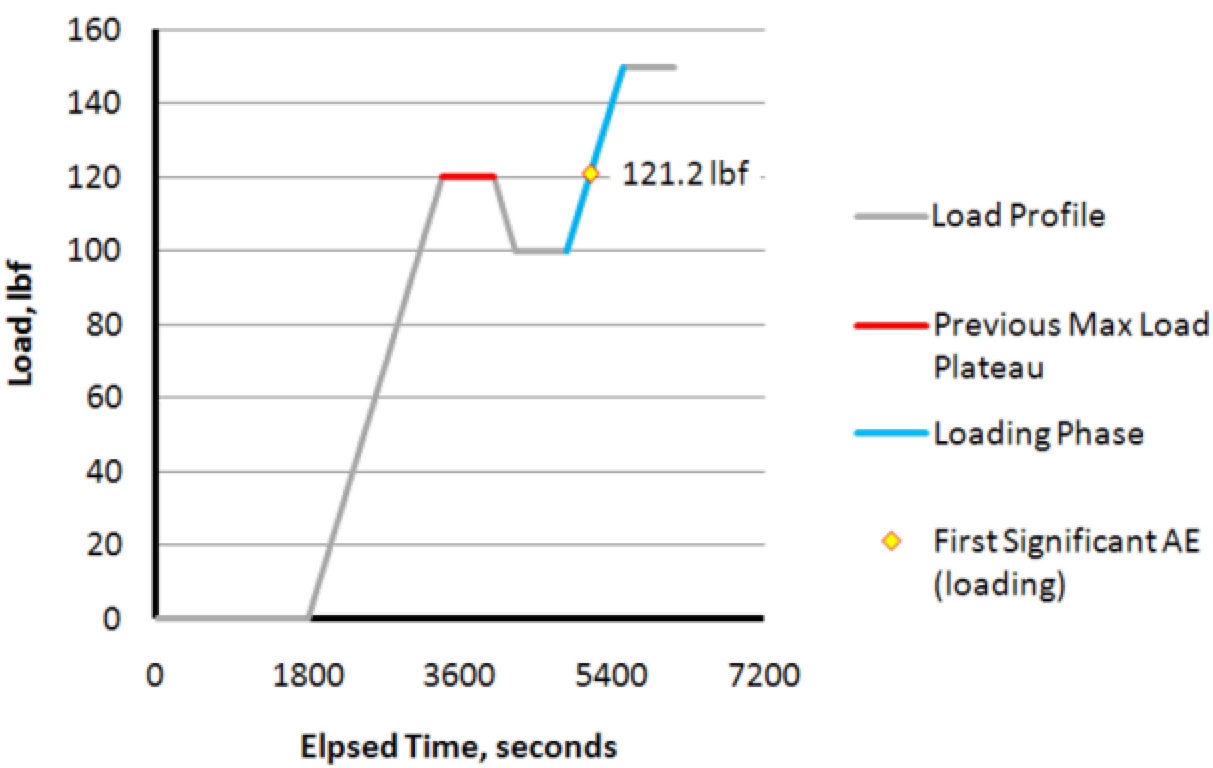
Final Week of COPV Test Before Rupture



Felicity ratio (FR)

- Felicity ratio (*FR*) coupled with AE feature analysis, especially peak frequency and energy, shows promise as analytical pass/fail criteria

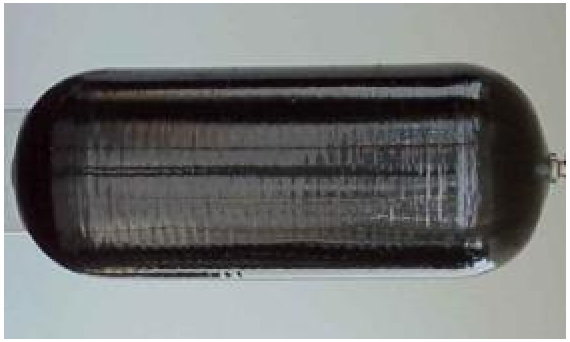
$$FR = \frac{stress\ at\ onset\ of\ significant\ acoustic\ emission\ during\ loading}{maximum\ previous\ stress\ plateau}$$



$$FR = \frac{121.2}{120} = 1.01$$

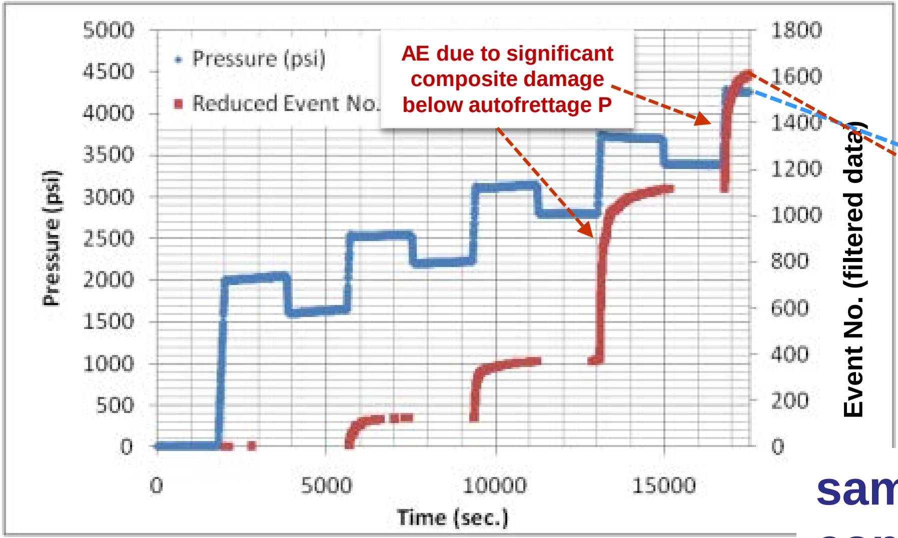
Results & Discussion

A 6.3-in. diameter IM-7 COPV was subjected to an ILH pressure schedule at LR ≈ 0.3 to 0.9

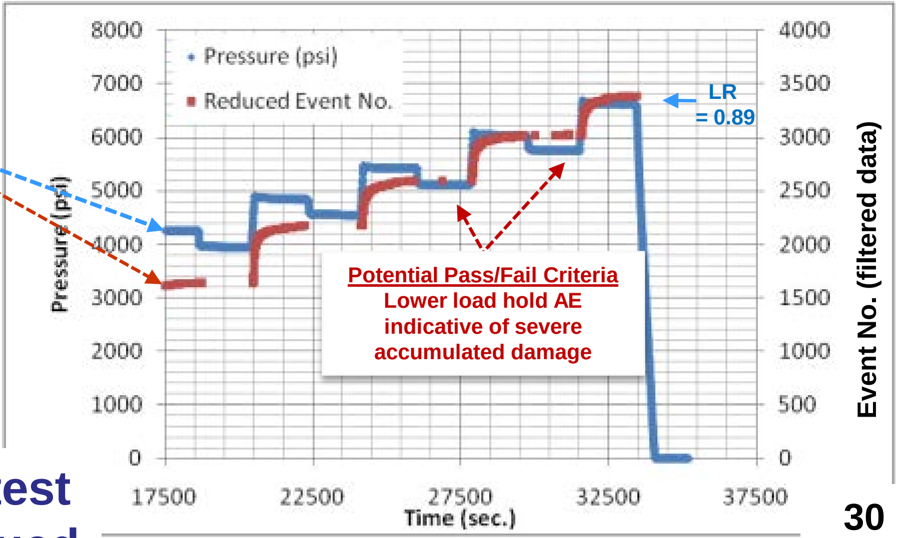


Pressure & Events vs. Time

0 to 17500 s

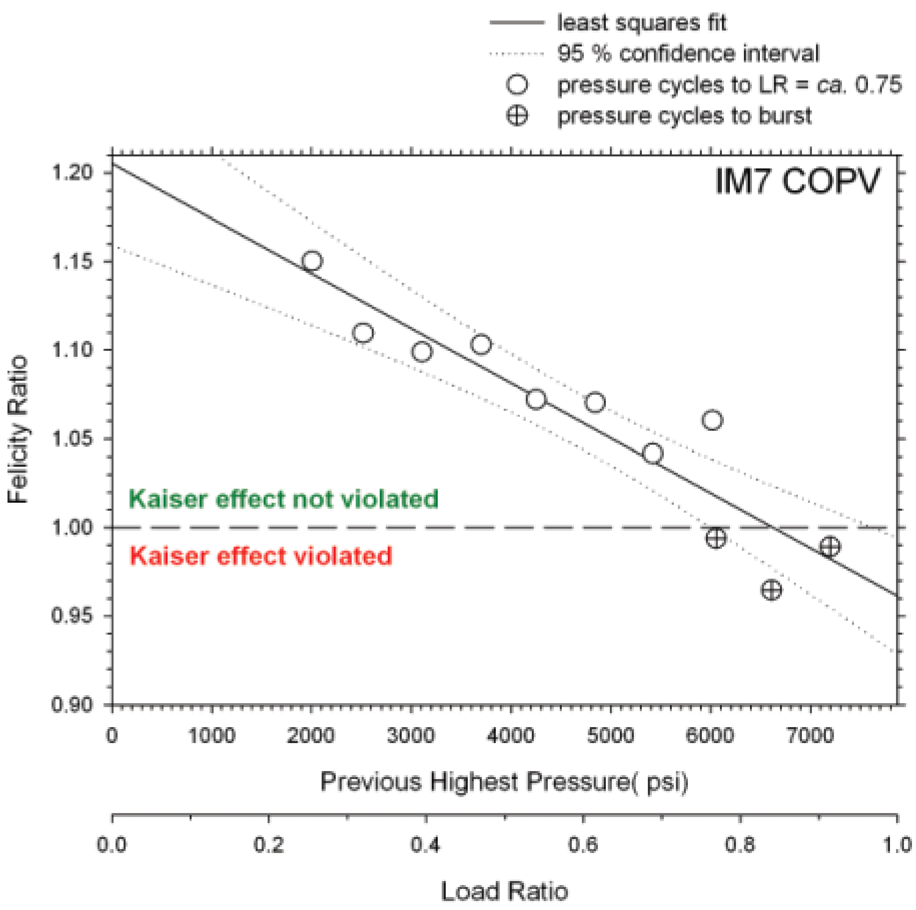


17500 to 37500 s (cont.)



same test continued

Example COPV Test

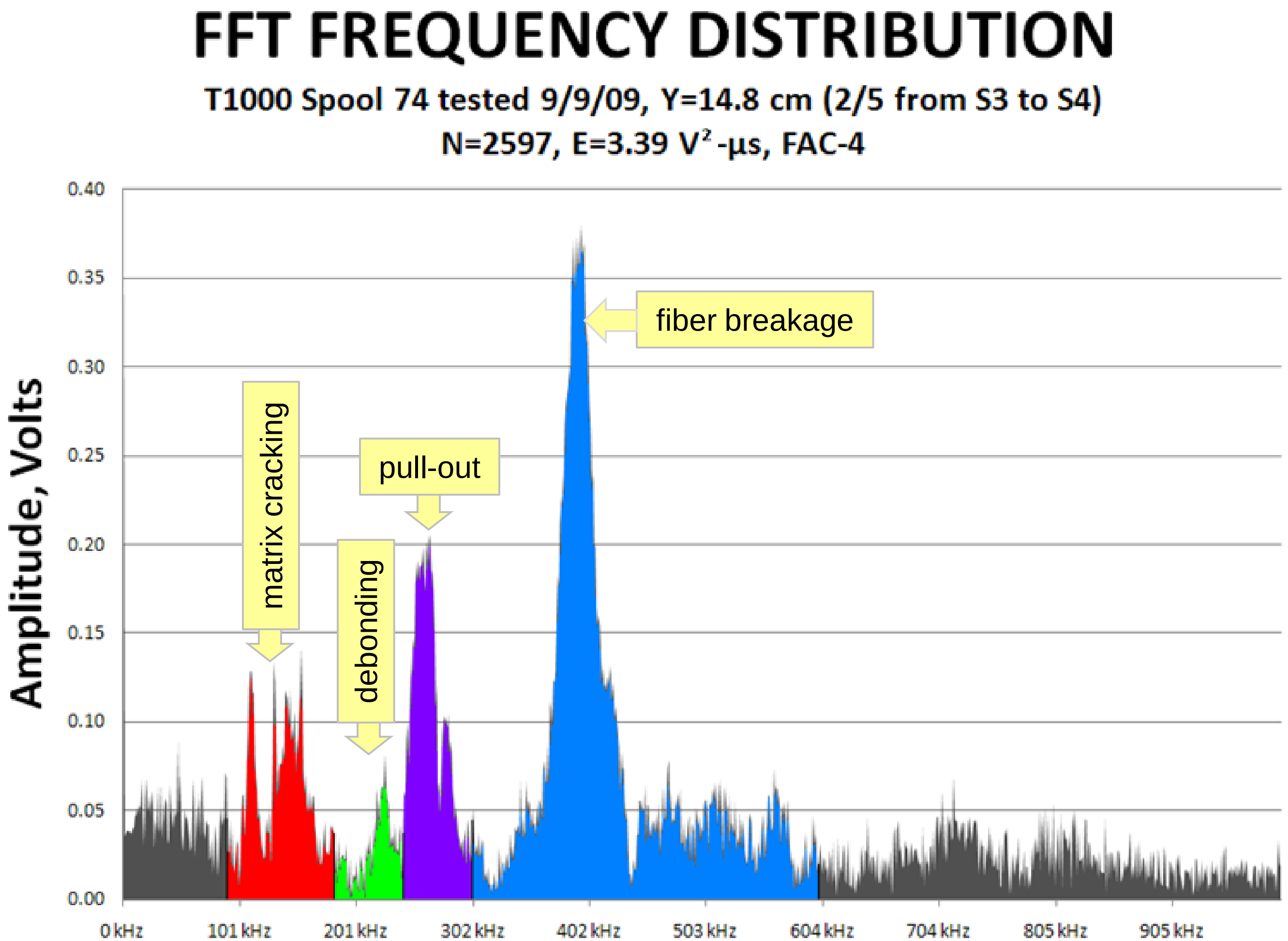


<u>Potential Pass/Fail Criteria</u>
FR < 1; The true limit is structurally dependant (0.95-0.99).

Felicity ratio results for an IM7 composite overwrapped pressure vessel pressurized to 6800 psi and then to burst at 7870 psi

Results & Discussion

FFT (unfiltered) showing concerted failure using De Groot's frequency ranges



Software Developed to Support Analysis

- Analyzing AE data without the aid of sophisticated software is time consuming and occasionally introduces human error due to the complexities involved
  - To circumvent these issues, an algorithm was developed to reduce the AE data and automatically predict the critical rupture point
  - An extensive validation process has been undertaken to increase the versatility and accuracy of the algorithm
  - A graphical user interface is also being developed to allow real-time analysis of pressurized (stressed) systems
  - Integration of many of these algorithms to NASA software (NDEWIP) is ongoing

- Specific features of the algorithm include automatic AE data filtering and synchronization of the AE and pressure data.
  - This algorithm also checks the linearity of the *FR* vs. previous highest-pressure data using several different averaging methods for determining the onset of significant AE (*FR* nominator), selecting the best (optimal) averaging method to use for the existing AE data set

COPV Preparation for Testing

Conventional strain gauges installed near fiber
Bragg gratings, relative to laser profilometry map

Carbon Stress Rupture Test System

20 Carbon Vessels and real-time NDE in WSTF Lexan protective enclosure allows inspection while at test pressure

NDE Needs for Propulsion System Inspections

NDE Needs for Propulsion System Inspections

- On-orbit
  - Inspection of potential damage from Micrometeorite and Orbital Debris impacts (exposed engine nozzles and pressurized structures)
  - Inspection and manipulation behind rack and in hidden places

- Liquid Engines and components
  - Interface port inspections during installation
  - Barrier coating inspections and damage measurement
  - Injector flow visualization
  - Cooled nozzles and regenerative cooling section integrity inspections
  - Ground test plume characterizations and mass flow evaluation

NDE Needs for Propulsion System Inspections

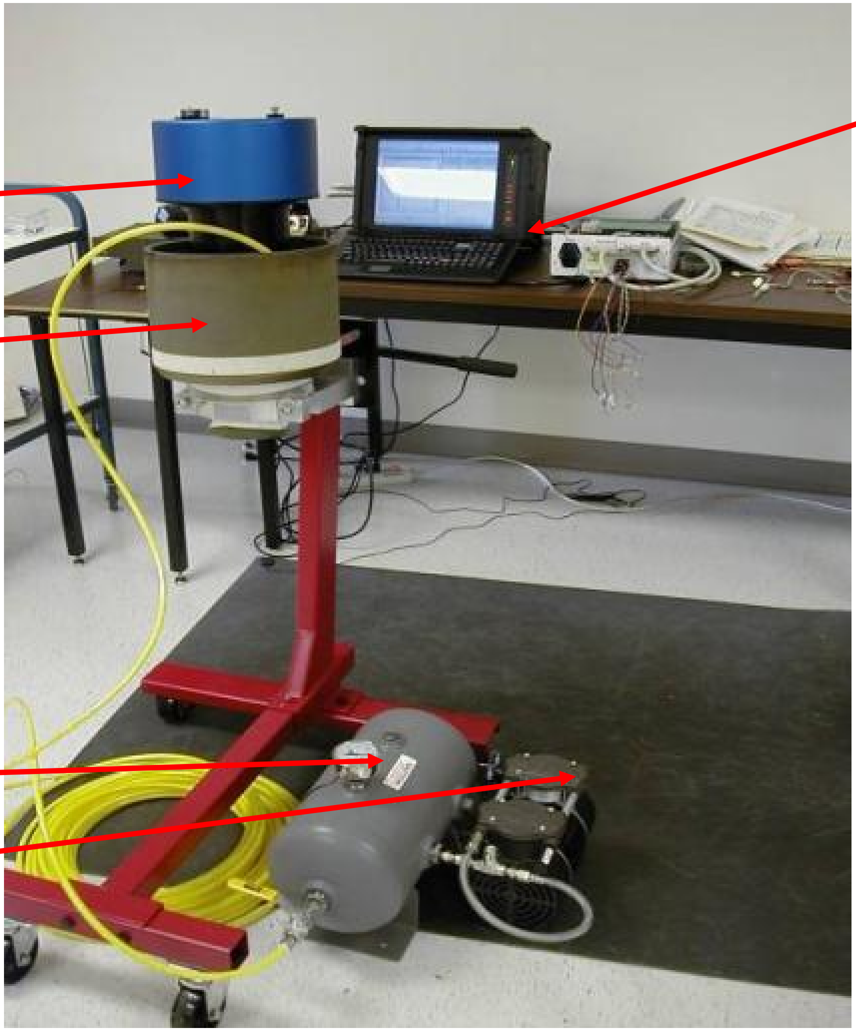
- Solid Rocket Motors
  - Composite cases integrity inspections (similar to COPVs)
  - Propellant defects such as cracks, tears, voids, porosity, foreign material inclusion and port deformation
  - Interface defects such as debonds, delaminations, and resin filling defects

- Pyrotechnics
  - Separation joint charge position - optimized x-ray
  - Pyrotechnic charge, nonmetallic seals, and adhesive bonds generally use N-ray to better emphasize non metallics
  - Adhesive acreage bounds -focused UT/Acoustic Microscopy scanning
  - Ground test - High Speed imaging and Optical Pyrometers

Example Laser Combustion Chamber Mapping System

Laser Scanner

Thruster



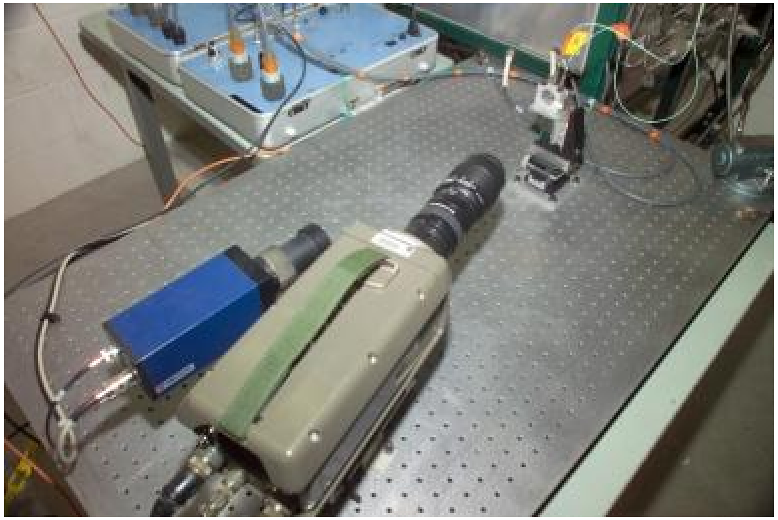
Ruggedized and man portable computer & controller

Vacuum Tank

Pump

High Speed Optical Pyrometer

- High speed imaging and temperature measurement of pyrotechnic events though robust sapphire windows
  - 10 µs temperature response



Rocket Engine Testing Needs

The following techniques should improve test operations:

- Robotic Inspection Snake
  - Injector surfaces and chambers generally need inspection following a firing and it is desirable not contact any surfaces or put humans in “harms way” from residual toxic propellants or other hazards.
  - Inspection of complex piping systems .
    - Includes the chemical steam generator system fluid lines
    - Inspection of exhaust piping
- Free flier inspection camera
  - Would be useful for inspection of facility locations that are hard to reach due to lack of platforms and ladders (similar and possibly more significant need in-space though)
- Handheld backscatter x-ray
  - Would benefit inspection of composite nozzles and chambers and may have application to imaging under test conditions.

Backup Slides

Contributing Information

- 4th IAASS Conference - Making Safety Matter , Nondestructive Evaluation and Monitoring Results from COPV Accelerated Stress Rupture Testing, NASA White Sands Test Facility (WSTF) (No. 1878627)
- *Use of Modal Acoustic Emission to Monitor Damage Progression in Carbon Fiber/Epoxy Tows and Implications for Composite Structures, ASNT Fall Conference & Quality Testing Show, NASA NDE II Houston, TX*
- *New ASTM Standards for Nondestructive Testing of Aerospace Composites, ASNT Fall Conference & Quality Testing Show, NASA NDE II Houston, TX Jess M. Waller and Regor L. Saulsberry NASA-JSC White Sands Test Facility*
  48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA-2007-2324 , Overview: Nondestructive Methods and Special Test Instrumentation Supporting NASA Composite Overwrapped Pressure Vessel (COPV) Assessments
- *NDE Methods for Certification and Production/Performance Monitoring of Composite Tanks, David McColskey, Marvin Hamstad, Regor Saulsberry, Jess Waller*
- Shearography NDE of Composite Over-Wrapped Pressure Vessels (COPVs), ASNT Fall Conference 2007
  Survey of Nondestructive Methods Supporting Shuttle and ISS Composite Overwrapped Pressure Vessel (COPV) Testing, Aging Aircraft Conference , 2006

Contributing Information

- G.P. Sutton & O. Biblarz, Rocket Propulsion Elements, 7th Ed., John Wiley & Sons, Inc., New York, 2001, ISBN 0-471-32642-9. 2. D.K. Huzel & D.H. Huang, Modern Engineering for Design of Liquid-Propellant Rocket Engines, Vol 147, Progress in Astronautics and Aeronautics, Published by AIAA, Washington DC., 1992, ISBN 1-56347-013-6. 3. V. Yang, T. B. Brill, W.-Z. Ren, Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics, Published by AIAA, Washington DC, 2000, ISBN 1-56347-442-5 4. F.-K. Chang, ed., Structural Health Monitoring 2005, DEStech Publications, 2005, ISBN 1-932078-51-7

Relevant Literature (non-inclusive list)

1. **AIAA**
   - **S-080 Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components**
   - **S-081A Space Systems - Composite Overwrapped Pressure Vessels (COPVs)**
2. **ASME**
   - **STP-PT-021 Non Destructive Testing and Evaluation Methods for Composite Hydrogen Tanks**
3. **ASTM**
   - **E 1419 Test Method for Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission**
   - **E 1736 Practice for Acousto-Ultrasonic Assessment of Filament-Wound Pressure Vessels**
   - **E 2191 Test Method for Examination of Gas-Filled Filament-Wound Composite Pressure Vessels Using Acoustic Emission**
   - **E 2581 Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications**
4. **ISO**
   - **14623 Space Systems - Pressure Vessels and Pressurized Structures - Design and Operation** (similar to AIAA S-080 and -081, and NASA-STD-5009)
5. **NASA**
   - **MSFC-RQMT-3479 Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures**
   - **NASA-STD-5007 General Fracture Control Requirements for Manned Spaceflight Systems**
   - **NASA-STD-5009 Nondestructive Evaluation Requirements For Fracture Control Programs**
     - **JSC Special Addendum Physical Crack Standard**
   - **NASA-STD-5019 Fracture Control Requirements for Spaceflight Hardware**
   - **NASA-STG-5014 Nondestructive Evaluation (NDE) Implementation Handbook for Fracture Control Programs (draft)**
6. **Miscellaneous**
   - **AFSPCMAN 91-710**
   - **CSA NGV2-2000 Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers**
   - **KHB 1710.2D**
   - **MIL-STD-1522 Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems**

Background – ASTM E07.10 TG of NDE of Aerospace Composites

- In late 2004, NASA took the lead in initiating efforts to develop national voluntary consensus standards for NDE of aerospace composite materials, components and structures
- ASTM Task Group (TG) for NDE of Aerospace Composites formed in January 2005 (under ASTM E07.10)
- The TG has been meeting twice a year since formation:
  - currently comprised of 116 members
  - chaired by George Matzkanin from TRI/Austin
  - other principals include Jess Waller and Regor Saulsberry, NASA-JSC White Sands Test Facility; and Tom Yolken, TRI/Austin
- Initial focus was on polymer matrix composite material with relatively simple geometries such as flat panel laminates
- Current focus is on composite components with more complex inspection geometries, specifically COPVs
  - metallic liner (WK 29068)
  - composite overwrap (WK 29034)
  - liner/overwrap interface
  - Guide (TBD)

Background – ASTM Standards Developed Since 2005 and Current Plan

2005

2010

2011

2012

2013

Designation: E 2533 – 09

Standard Guide for
Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications[1]

Designation: E 2580 – 07

Standard Practice for
Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2582 – 07

Standard Practice for
Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

Designation: E 2581 – 07

Standard Practice for
Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

Designation: E 2662 – 09

Standard Practice for
Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E2661/E2661M – 10

Standard Practice for
Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

NDE of Flat Panel Composite Standard Practices and Guide

5-year re-approval of E2580, E2580 and E2581

ASTM WK29034

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29034 - New Practice for Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

ASTM WK29068

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29068 - New Practice for Examination of the Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

NDE of COPV Standard Practices, Feasibility of NDE of COPV Guide

Many collaborations and partnerships formed out of the 2009 Composite Pressure Vessel Summit

http://www.nasa.gov/centers/wstf/news/safetysummit2009.html